

PROGRESS REPORT

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Report Covering the Period: 1/25/96 - 1/24/97

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PROGRESS REPORT (1/25/96 to 1/24/97)

NASA Grant NAG5-3224

PI: Stephen L. Skinner (JILA)

Sponsoring PI: Jeffrey L. Linsky (JILA)

Grant Identification - NASA NAG5-3224 funds the research of Stephen L. Skinner under the LTSA program. The proposal title was *X-ray Emission from Pre-Main-Sequence Stars - Testing the Solar Analogy*.

Start Date - The first year of this fellowship commenced at JILA on 25 April 1995.

Report Period - This report covers the period 25 January 1996 - 24 January 1997.

Research Synopsis - This LTSA award funds my research on the origin of X-ray emission from pre-main-sequence stars, with emphasis on low-mass T Tauri stars (≤ 2 solar masses) and the more massive Herbig Ae/Be stars ($\sim 2 - 10$ solar masses). The focus continues to be on the reduction and analysis of data on young stars acquired recently by the *ASCA* observatory (Advanced Satellite for Cosmology and Astrophysics). This work has been undertaken in collaboration with Dr. M. Güdel (PSI/ETH Zurich) and with astronomers at ISAS in Japan (esp. Drs. K. Koyama, F. Nagase, and S. Yamauchi).

During this reporting period, several *ASCA* observations were analyzed and brought to publication. These include (i) an observation of the Barnard 209 dark cloud in the nearby Taurus star-forming region, which detected an exceptional X-ray flare in the young T Tauri binary system V773 Tau (Skinner et al. 1997), (ii) an analysis of the X-ray emission measure distribution of the G0V star EK Draco, which is believed to be an analog of the young Sun (Güdel et al. 1997), and (iii) a study of the time-evolution of coronal properties of young solar-like stars (Güdel, Guinan, & Skinner 1997). Other papers which are nearing completion include an analysis of recent *ASCA* data of the unusual Wolf-Rayet system HD50896 (= EZ CMa), which is one of the few known WR systems suspected to harbor a compact companion (e.g. neutron star). This latter study is the culmination of work that was initiated while I was a post-doc at ISAS in Tokyo.

Research on Herbig Ae/Be Stars - The paper *ASCA Observations of HD104237 and the Origin of X-ray Emission from Herbig Ae/Be Stars* by S. Skinner and S. Yamauchi appeared in the 1996 November 10 issue of ApJ.

Research on T Tauri Stars - I have completed an in-depth analysis of two *ASCA* pointings of the nearby Barnard 209 dark cloud in the Taurus-Auriga region (distance = 150 pc) and the results have recently been submitted to ApJ (Skinner et al 1997). The B209 cloud is an active star-forming region that contains several young T Tauri stars as well as heavily obscured infrared sources that are thought to be young stars still in the act of forming. These objects are probably analogous to the young sun and their study offers us an indirect means of inferring what the sun may have been like in its formative stage.

The above paper presents the most detailed analysis ever conducted of an X-ray flare on a T Tauri star. The V773 Tau flare is one of the strongest ever detected on a T Tauri star and has a peak X-ray luminosity that exceeds that of the quiet sun by five orders of magnitude. Using time-resolved *ASCA* spectra, we present the first reconstruction of the evolution of temperature and emission measure during the decay of a flare on a T Tauri star. Our high signal-to-noise spectra show conclusively that the variability during the flare is strictly associated with a superhot plasma component whose maximum temperature exceeded 40 million K. More interestingly, the decay of the *ASCA* light curve shows a sinusoidal profile which suggests that the volume containing the flaring plasma was being progressively occulted by stellar rotation. Furthermore, the *ASCA* data clearly show that the flaring plasma was being reheated by low-level secondary events during the main decay. The above new results show that X-ray flares on T Tauri stars involve complex phenomena that may include reheating of the post-flare plasma and dynamical

effects superimposed on the flare decay profile. These complexities must be considered when assessing flare properties and when attempting to make comparisons with solar X-ray flares.

Other work that is still in progress includes an analysis of a 30 ksec *ASCA* observation of the upper Scorpius association, which includes numerous T Tauri stars. This work is being done in collaboration with Dr. Fred Walter (SUNY) and a draft paper has been written. The paper will be submitted to ApJ in 1997.

Research on Young Solar-like G Stars - This has been a very active research area for me during this reporting period. In collaboration with M. Güdel, several papers have been submitted to ApJ that discuss the X-ray properties of young stars and compare them with the sun. Specifically, we have analyzed the coronal X-ray properties of nine solar-like stars of spectral type G that span a range of ages from 70 million years up to ~ 9 billion years (Güdel, Guinan, & Skinner 1997). In a related paper, we have presented a more detailed discussion of the coronal emission of the youngest star in this sample, EK Draconis (Güdel et al 1996). Using *ASCA* and *ROSAT* data we find that the coronae of these nine stars are all well-described by a two-temperature distribution with a hot component at $\sim 20 - 30$ million K and a cool component at $\sim 1 - 10$ million K. Our analysis indicates that the amount of hot plasma at flare-like temperatures decays with age (or, equivalently, the X-ray luminosity associated with the hot component decays with age). These results support the belief that coronal activity declines with age and that the young sun was much more active than it is today. This latter point has important implications for X-irradiation of the solar protoplanetary nebula.

X-ray Emission from Massive Stars - In contrast to X-ray emission from low-mass stars, which is generally believed to arise in hot magnetically-confined plasma, the origin of X-ray emission in massive stars is much more obscure. The conventional interpretation has been that the X-ray emission of massive OB and Wolf-Rayet stars originates in wind shocks. However, recent results are beginning to raise questions about the general validity of this interpretation. To place better constraints on the origin of X-ray emission in massive stars, we have been acquiring *ASCA* observations of selected Wolf-Rayet stars. I am now analyzing *ASCA* data for the WR star HD50896 (EZ CMa) in collaboration with Dr. F. Nagase (ISAS) and Dr. M. Itoh (Kobe U.). Several authors have suggested that this WR star may have a compact companion (cc), being either a neutron star or a low-mass black hole. Evolutionary scenarios do predict that WR + cc systems should arise from progenitor O + O binary systems via mass transfer and a subsequent supernova explosion. However, the identification of such WR + cc systems has been elusive, with Cyg X-3 being the only well-documented example. Thus, to test stellar evolution theories, detailed scrutiny of additional candidate WR + cc systems such as HD50896 is needed.

Our preliminary results show that HD50896 has a rather soft X-ray spectrum and no large-amplitude variability was detected down to a sensitivity-limited time resolution of 512 seconds. The X-ray luminosity is roughly an order of magnitude below that expected for wind accretion onto a neutron star companion. Thus, X-ray emission via accretion onto a neutron star companion seems unlikely. We are currently examining other alternatives, including X-ray emission from a black-hole accretion wake as well as more traditional interpretations involving wind shocks. Preliminary results of this study were presented at the Toronto AAS meeting in January 1997 and final results will be submitted in 1997 to ApJ or PASJ.

PUBLICATIONS RELATED TO THIS LTSA RESEARCH PROGRAM

Stephen L. Skinner

- Skinner, S.L., Güdel, M., Koyama, K., & Yamauchi, S., 1997, *ASCA Observations of the Barnard 209 Dark Cloud and an Intense X-ray Flare on V773 Tau*, ApJ, submitted.
- Skinner, S., Nagase, F., Ozawa, H., & Itoh, M., 1997, *ASCA Observations of the Unusual Wolf-Rayet Star HD 50896 (= EZ CMa)*, BAAS, 28(4), 1375.
- Güdel, M., Guinan, E.F., & Skinner, S.L., 1997, *The X-ray Sun in Time: A Study of the Long-term Evolution of Solar-type Coronae with ROSAT and ASCA*, ApJ, in press.
- Skinner, S.L., 1996, *Time-Resolved X-ray Spectroscopy of the Weak-lined T Tauri Star V773 Tau*, BAAS, 28(2), 884.
- Güdel, M., Guinan, E.F., Mewe, R., Kaastra, J.S., & Skinner, S.L., 1997, *A Determination of the Coronal Emission Measure Distribution in the Young Solar Analog EK Draconis from ASCA/EUVE Spectra*, ApJ, in press.
- Stevens, I.R., Corcoran, M.F., Willis, A.J., Pollock, A.M.T., Skinner, S.L., Nagase, F., & Koyama, K., 1996, *ASCA Observations of γ^2 Velorum (WC8 + O9I): The Variable X-ray Spectrum of Colliding Winds*, MNRAS, 283, 589.
- Güdel, M., Benz, A.O., Schmitt, J.H.M.M., & Skinner, S.L., 1996, *The Neupert Effect in Active Stellar Coronae: Chromospheric Evaporation and Coronal Heating in the dMe Flare Star Binary UV Ceti*, ApJ, 471, 1002.
- Skinner, S., & Yamauchi, S., 1996, *ASCA Observations of HD104237 (A4e) and the Origin of X-ray Emission from Herbig Ae Stars*, ApJ, 471, 987.
- Stevens, I., Skinner, S., Nagase, F., Corcoran, M., Willis, A., Pollock, A., & Koyama, K., 1995, *ASCA Observations of Colliding Stellar Winds in γ Velorum*, Ap. & Space Sci., 224, 569.
- Skinner, S., Walter, F., & Yamauchi, S., 1995, *ASCA Observations of Pre-Main-Sequence Stars*, in *Röntgenstrahlung from the Universe*, eds. H. Zimmermann & J. Trümper, Garching: ESO, 69.
- Güdel, M., Guinan, E., & Skinner, S., 1995, *ROSAT/ASCA/VLA Studies of Solar Proxies*, in *Röntgenstrahlung from the Universe*, *ibid.*, 39.
- Güdel, M., Guinan, E., Skinner, S., & Linsky, J., 1995, *The Hot Corona of YY Mensae*, in *Röntgenstrahlung from the Universe*, *ibid.*, 33.
- Skinner, S. & Brown, A., 1995, *ASCA X-ray Spectra of Late-type Giants and Supergiants: the Active G Star β Draconis*, in *Ninth Cambridge Workshop on Cool Stars, Stellar Systems and the Sun*, eds. R. Pallavicini and A. Dupree, San Francisco: ASP, 291.
- Brown, A., & Skinner, S., 1995, *A Comparative Analysis of Simultaneous ASCA and EUVE Spectroscopy of the RS CVn Binary HR1099*, in *Ninth Cambridge Workshop on Cool Stars, Stellar Systems and the Sun*, *ibid.*, 255.

Güdel, M., Guinan, E., & Skinner, S., 1995, *The Sun in Time: Coronal Structuring and Evolution*, in Ninth Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, *ibid.*, 607.

Brown, A., Skinner, S.L., Stewart, R.T., & Jones, K.L., 1995, *Simultaneous X-ray, EUV, UV, and Radio Observations of the RS CVn Binary HR1099*, eds. Y. Uchida, T. Kosugi, & H.S. Hudson (Dordrecht: Kluwer), 279.